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High-Voltage Switching Equipment

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The design of the high-voltage substation must include consideration for the safe operation and maintenance of the equipment. Switching equipment is used to provide isolation, no load switching, load switching, and/or interruption of fault currents. The magnitude and duration of the load and fault currents will be significant in the selection of the equipment used.

System operations and maintenance must also be considered when equipment is selected. One significant choice is the decision of single-phase or three-phase operation. High-voltage power systems are generally operated as a three-phase system, and the imbalance that will occur when operating equipment in a single-phase mode must be considered.

4.1 Ambient Conditions

Air-insulated high-voltage electrical equipment is generally covered by standards based on assumed ambient temperatures and altitudes. Ambient temperatures are generally rated over a range from -40°C to $+40^{\circ}\text{C}$ for equipment that is air insulated and dependent on ambient cooling. Altitudes above 1000 meters (3300 feet) may require derating.

At higher altitudes, air density decreases, hence the dielectric strength is also reduced and derating of the equipment is recommended. Operating (strike distances) clearances must be increased to compensate for the reduction in dielectric strength of the ambient air. Also, current ratings generally decrease at higher elevations due to the decreased density of the ambient air, which is the cooling medium used for dissipation of the heat generated by the load losses associated with load current levels.

4.2 Disconnect Switches

A disconnect switch is a mechanical device used to change connections within a circuit or isolate a circuit from its power source, and is normally used to provide isolation of the substation equipment for

maintenance. Typically a disconnect switch would be installed on each side of a piece of equipment to provide a visible confirmation that the power conductors have been opened for personnel safety. Once the switches are placed in the open position, safety grounds can be attached to the de-energized equipment for worker protection. Switches can be equipped with grounding blades to perform the safety grounding function.

Disconnect switches are designed to continuously carry load currents and momentarily carry higher capacity for short-circuit currents for a specified duration (typically specified in seconds). They are designed for no load switching, opening or closing circuits where negligible currents are made or interrupted, or when there is no significant voltage across the open terminals of the switch. They are relatively slow-speed operating devices and therefore are not designed for arc interruption. Disconnect switches are also installed to bypass breakers or other equipment for maintenance and can also be used for bus sectionalizing. Interlocking equipment is available to prevent inadvertent operating sequence by inhibiting operation of the disconnect switch operation until the fault and/or load currents have been interrupted by the appropriate equipment.

Single-phase or three-phase operation is possible for some switches. Operating mechanisms are normally installed to permit operation of the disconnect switch by an operator standing at ground level. The operating mechanisms provide a swing arm or gearing to permit operation with reasonable effort by utility personnel. Motor operating mechanisms are also available and are applied when remote switching is necessary.

Disconnect switch operation can be designed for vertical or horizontal operating of the switch blades. Several configurations are frequently used for switch applications including:

- Vertical break
- Double break switches
- V switches
- Center break switches
- Hook stick switches
- Vertical reach switches
- Grounding switches

Phase spacing is usually adjusted to satisfy the spacing of the bus system installed in the substation.

4.3 Load Break Switches

A load break switch is a disconnect switch that has been designed to provide making or breaking of specified currents. This is accomplished by addition of equipment that increases the operating speed of the disconnect switch blade and the addition of some type of equipment to alter the arcing phenomena and allow the safe interruption of the arc resulting when switching load currents.

Disconnect switches can be supplied with equipment to provide a limited load switching capability. Arcing horns, whips, and spring actuators are typical at lower voltages. These switches are used to de-energize or energize a circuit that possesses some limited amount of magnetic or capacitive current, such as transformer exciting current or line charging currents.

An air switch can be modified to include a series interrupter (typically vacuum or SF₆) for higher voltage and current interrupting levels. These interrupters increase the load break capability of the disconnect switch and can be applied for switching load or fault currents of the associated equipment.

4.4 High-Speed Grounding Switches

Automatic high-speed grounding switches are applied for protection of transformer banks when the cost of supplying other protective equipment is too costly. The switches are generally actuated by discharging a spring mechanism to provide the “high-speed” operation. The grounding switch operates to provide

a deliberate ground on the high-voltage bus supplying the equipment (generally a transformer bank), which is detected by protective relaying equipment remotely, and operates the transmission line breakers at the remote end of the line supplying the transformer. This scheme also imposes a voltage interruption to all other loads connected between the same remote breakers. A motor-operated disconnect switch is frequently installed along with a relay system to sense bus voltage and allow operation of a motor-operated disconnect switch when there is no voltage on the transmission line to provide automatic isolation of the faulted bank, and allow reclosing operation of the remote breaker to restore service to the transmission line.

The grounding switch scheme is dependent on the ability of the source transmission line relay protection scheme to recognize and clear the fault by opening the remote line circuit breaker. Clearing times are necessarily longer since the fault levels are not normally within the levels appropriate for an instantaneous trip response. The lengthening of the trip time also imposes additional stress on the equipment being protected and should be considered when selecting this method for bank protection. Grounding switches are usually considered when relative fault levels are low so that there is not the risk of significant damage to the equipment with the associated extended trip times.

4.5 Power Fuses

Power fuses are a generally accepted means of protecting power transformers in distribution substations. The primary purpose of a power fuse is to provide interruption of permanent faults. Fusing is an economical alternative to circuit switcher or circuit breaker protection. Fuse protection is generally limited to voltages from 34.5 kV through 69 kV, but has been applied for protection of 115-kV and 138-kV transformers.

To provide the greatest protective margin, it is necessary to use the smallest fuse rating possible. The advantage of close fusing is the ability of the fuse unit to provide backup protection for some secondary faults. For the common delta-wye connected transformer, a fusing ratio of 1.0 would provide backup protection for a phase-to-ground fault as low as 230% of the secondary full-load rating. Fusing ratio is defined as the ratio of the fuse rating to the transformer full load current rating. With low fusing ratios, the fuse may also provide backup protection for line-to-ground faults remote to the substation on the distribution network.

Fuse ratings also must consider parameters other than the full load current of the transformer being protected. Coordination with other overcurrent devices, accommodation of peak overloads, and severe duty may require increased ratings of the fuse unit. The general purpose of the power transformer fuse is to accommodate, not interrupt, peak loads. Fuse ratings must consider the possibility of nuisance trips if the rating selected is too low for all possible operating conditions.

The concern of unbalanced voltages in a three-phase system must be considered when selecting fusing for power transformer protection. The possibility of one or two fuses blowing must be reviewed. Unbalanced voltages can cause tank heating in three-phase transformers and overheating and damage to three-phase motor loads. The potential for ferroresonance must be considered for some transformer configurations when using fusing.

Fuses are available in a number of tripping curves (standard, slow, and very slow) to provide coordination with other system protective equipment. Fuses are not voltage-critical; they may be applied at any voltage equal to or greater than their rated voltage. Fuses may not require additional structures, and are generally mounted on the incoming line structure, resulting in space savings in the substation layout.

4.6 Circuit Switchers

Circuit switchers have been developed to overcome some of the limitations of fusing for substation transformers. They are designed to provide three-phase interruption (solving the unbalanced voltage considerations) and provide protection for transient overvoltages and overloads at a competitive cost

between the costs of fuses and circuit breakers. Additionally, they can provide protection from transformer faults based on differential, sudden pressure, and overcurrent relay schemes as well as critical operating constraints such as low oil level, high oil or winding temperature, pressure relief device operation, and others.

Circuit switchers are designed and supplied as a combination of a circuit breaking interrupter and an isolating disconnect switch. Later models have been designed with improved interrupters that have reduced the number of gaps and eliminated the necessity of the disconnect switch blades in series with the interrupter. Interrupters are now available in vertical or horizontal mounting configurations, with or without an integral disconnect switch. Circuit switchers have been developed for applications involving protection of power transformers, lines, capacitors, and line connected or tertiary connected shunt reactors.

Circuit switchers are an alternative to the application of circuit breakers for equipment protection. Fault duties may be lower and interrupting times longer than a circuit breaker. Some previous designs employed interrupters with multiple gaps and grading resistors and the integral disconnect switch as standard. The disconnect switch was required to provide open-circuit isolation in some earlier models of circuit switchers.

Circuit switchers originally were intended to be used for transformer primary protection. Advancements in the interrupter design have resulted in additional circuit switcher applications, including:

- Line and switching protection
- Cable switching and protection
- Single shunt capacitor bank switching and protection
- Shunt reactor switching and protection (line connected or tertiary connected reactors)

4.7 Circuit Breakers

A circuit breaker is defined as “a mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying and breaking for a specified time, and breaking currents under specified abnormal circuit conditions such as a short circuit” (IEEE Std. C37.100-1992).

Circuit breakers are generally classified according to the interrupting medium used to cool and elongate the electrical arc permitting interruption. The types are:

- Air magnetic
- Oil
- Air blast
- Vacuum
- SF6 gas

Air magnetic circuit breakers are limited to older switchgear and have generally been replaced by vacuum or SF6 for switchgear applications. Vacuum is used for switchgear applications and some outdoor breakers, generally 38 kV class and below. Air blast breakers, used for high voltages (≥ 765 kV), are no longer manufactured and have been replaced by breakers using SF6 technology.

Oil circuit breakers have been widely used in the utility industry in the past but have been replaced by other breaker technologies for newer installations. Two designs exist — bulk oil (dead-tank designs) dominant in the U.S.; and oil minimum breaker technology (live-tank design). Bulk oil circuit breakers were designed as single-tank or three-tank mechanisms; generally, at higher voltages, three-tank designs were dominant. Oil circuit breakers were large and required significant foundations to support the weight and impact loads occurring during operation. Environmental concerns forcing the necessity of oil retention systems, maintenance costs, and the development of the SF6 gas circuit breaker have led to the gradual replacement of the oil circuit breaker for new installations.

Oil circuit breaker development has been relatively static for many years. The design of the interrupter employs the arc caused when the contacts are parted and the breaker starts to operate. The electrical arc generates hydrogen gas due to the decomposition of the insulating mineral oil. The interrupter is designed to use the gas as a cooling mechanism to cool the arc and to use the pressure to elongate the arc through a grid (arc chutes), allowing extinguishing of the arc when the current passes through zero.

Vacuum circuit breakers use an interrupter that is a small cylinder enclosing the moving contacts under a high vacuum. When the contacts part, an arc is formed from contact erosion. The arc products are immediately forced to and deposited on a metallic shield surrounding the contacts. Without anything to sustain the arc, it is quickly extinguished.

Vacuum circuit breakers are widely employed for metal-clad switchgear up to 38 kV class. The small size of the breaker allows vertically stacked installations of breakers in a two-high configuration within one vertical section of switchgear, permitting significant savings in space and material compared to earlier designs employing air magnetic technology. When used in outdoor circuit breaker designs, the vacuum cylinder is housed in a metal cabinet or oil-filled tank for dead tank construction popular in the U.S. market.

Gas circuit breakers generally employ SF₆ (sulfur hexafluoride) as an interrupting and sometimes as an insulating medium. In “single puffer” mechanisms, the interrupter is designed to compress the gas during the opening stroke and use the compressed gas as a transfer mechanism to cool the arc and to elongate the arc through a grid (arc chutes), allowing extinguishing of the arc when the current passes through zero. In other designs, the arc heats the SF₆ gas and the resulting pressure is used for elongating and interrupting the arc. Some older two-pressure SF₆ breakers employed a pump to provide the high-pressure SF₆ gas for arc interruption.

Gas circuit breakers typically operate at pressures between six and seven atmospheres. The dielectric strength of SF₆ gas reduces significantly at lower pressures, normally as a result of lower ambient temperatures. Monitoring of the density of the SF₆ gas is critical and some designs will block operation of the circuit breaker in the event of low gas density.

Circuit breakers are available as live-tank or dead-tank designs. Dead-tank designs put the interrupter in a grounded metal enclosure. Interrupter maintenance is at ground level and seismic withstand is improved vs. the live-tank designs. Bushings are used for line and load connections which permit installation of bushing current transformers for relaying and metering at a nominal cost. The dead-tank breaker does require additional insulating oil or gas to provide the insulation between the interrupter and the grounded tank enclosure.

Live-tank circuit breakers consist of an interrupter chamber that is mounted on insulators and is at line potential. This approach allows a modular design as interrupters can be connected in series to operate at higher voltage levels. Operation of the contacts is usually through an insulated operating rod or rotation of a porcelain insulator assembly by an operator at ground level. This design minimizes the quantity of oil or gas used for interrupting the arc as no additional quantity is required for insulation of a dead-tank enclosure. The design also readily adapts to the addition of pre-insertion resistors or grading capacitors when they are required. Seismic capability requires special consideration due to the high center of gravity of the interrupting chamber assembly.

Interrupting times are usually quoted in cycles and are defined as the maximum possible delay between energizing the trip circuit at rated control voltage and the interruption of the main contacts in all poles. This applies to all currents from 25 to 100% of the rated short-circuit current.

Circuit breaker ratings must be examined closely. Voltage and interrupting ratings are stated at a maximum operating voltage rating, i.e., 38 kV voltage rating for a breaker applied on a nominal 34.5-kV circuit. The breakers have an operating range designated as K factor per IEEE C37.06, (see Table 3 in the document's appendix). For a 72-kV breaker, the voltage range is 1.21, indicating that the breaker is capable of its full interrupting rating down to a voltage of 60 kV.

Breaker ratings need to be checked for some specific applications. Applications requiring reclosing operation should be reviewed to be sure that the duty cycle of the circuit breaker is not being exceeded.

Some applications for out-of-phase switching or back-to-back switching of capacitor banks also require review and may require specific-duty circuit breakers to insure proper operation of the circuit breaker during fault interruption.

4.8 GIS Substations

Advancements in the use of SF₆ as an insulating and interrupting medium have resulted in the development of gas insulated substations. Environmental and/or space limitations may require the consideration of GIS (gas-insulated substation) equipment. This equipment utilizes SF₆ as an insulating and interrupting medium and permits very compact installations.

Three-phase or single-phase bus configurations are normally available up to 145 kV class, and single-phase bus to 500 kV and higher, and all equipment (disconnect/isolating switches, grounding switches, circuit breakers, metering current, and potential transformers, etc.) are enclosed within an atmosphere of SF₆ insulating gas. The superior insulating properties of SF₆ allow very compact installations.

GIS installations are also used in contaminated environments and as a means of deterring animal intrusions. Although initial costs are higher than conventional substations, a smaller substation footprint can offset the increased initial costs by reducing the land area necessary for the substation.

4.9 Environmental Concerns

Environmental concerns will have an impact on the siting, design, installation, maintenance, and operation of substation equipment.

Sound levels, continuous as well as momentary, can cause objections. The operation of a disconnect switch, switching cables, or magnetizing currents of a transformer will result in an audible noise associated with the arc interruption in air. Interrupters can be installed to mitigate this noise. Closing and tripping of a circuit breaker will result in an audible momentary sound from the operating mechanism. Transformers and other magnetic equipment will emit continuous audible noise.

Oil insulated circuit breakers and power transformers may require the installation of systems to contain or control an accidental discharge of the insulating oil and prevent accidental migration beyond the substation site. Lubricating oils and hydraulic fluids should also be considered in the control/containment decision.

References

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